Special topic JPFR article
“Prospects of Research on Innovative Concepts in ITER Era”
contribution by M. Brown
Section 5.2.2

5.2.2 Dynamo and Reconnection Research:

Overview: Spheromaks undergo a relaxation process as they evolve towards a minimum energy state. Because of this, they are useful plasma configurations in which to study basic physical processes such as the dynamo and magnetic reconnection. Dynamo activity describes processes that convert plasma kinetic energy (such as flows and turbulence) to magnetic energy. Magnetic reconnection is the inverse process whereby energy stored in magnetic fields is rapidly converted back to kinetic energy (flows, turbulence, and ultimately heating). During the relaxation process, dynamo activity can be studied in the spheromak configuration. A fully relaxed spheromak is in a fundamental plasma state making the configuration useful for three dimensional reconnection studies.

Both the dynamo and reconnection have magnetohydrodynamic (MHD) descriptions but in the past few years, it has become apparent that a two-fluid theoretical description is needed to understand the observations. Studies of the dynamo and reconnection in the ITER era will focus on two-fluid or even full-particle descriptions of the physics. In the following section, we will discuss the role reconnection and the dynamo play in spheromaks.

Reconnection: Magnetic reconnection [Priest and Forbes, 2007] is the process by which oppositely directed magnetic flux in parcels of magnetized plasma is rapidly annihilated. Local annihilation of flux results in a global rearrangement of magnetic topology, plasma flows, and intense heating. In Nature, reconnection occurs when separate parcels of magnetofluid with oppositely directed magnetic field are merged [Brown, 1999]. Intense current sheets form at the interface of the merging parcels. It is in these boundary layers that magnetic flux is annihilated and plasma can be heated.

A spheromak is the simplest three dimensional parcel of flux, helicity, and magnetized plasma. Indeed, space and solar physicists have invoked the idea of spheromak-like force-free configurations in the solar corona and solar wind. The spheromak configuration is relatively easy to generate in the lab. Indeed, several formation schemes have been employed and all have generated a spheromak (plasma guns, flux cores, z-pinch, etc).

In the MHD model of reconnection due to Sweet and Parker [see Priest and Forbes, 2007], the width of the reconnection layer, δ, narrows until Ohmic dissipation due to finite conductivity, σ, just balances convection into the layer. A thin reconnection layer limits the outflow of plasma and flux so the MHD prediction of reconnection rate is very small. Both the thickness of the layer and the reconnection rate vanish like $S^{-1/2}$ where $S = \mu_0 V_A \ell \sigma$ is the Lundquist number and ℓ is the global scale. Even in a small laboratory plasma, the Lundquist number is large ($S \gg 10^3$), while in the solar corona, $S \gg 10^{12}$.

A more detailed, two-fluid description of reconnection includes the Hall terms in the generalized Ohm's law ($\mathbf{J} \times \mathbf{B}$ and $\nabla \mathbf{P}$). The two-fluid description predicts a broader reconnection layer scaling with the ion inertial length ($\delta_i = c/\omega_{pi}$) and a faster reconnection rate. Recent measurements from spheromak merging experiments have shown that the Hall terms indeed dominate resistive terms during reconnection events [Cothran, et al, 2005]. A final prediction of this model is that the reconnection current is carried by the electron fluid in a very thin layer in the reconnection zone. Field lines frozen to the electron fluid are swept out into a quadrupole pattern.

There are numerous instances of the natural occurrence of magnetic reconnection on the sun, in the solar wind, as well as in astrophysical objects [Brown, et al, 2006]. As an example, a particularly clear signature of magnetic reconnection was recently measured by the Polar spacecraft at the Earth's magnetopause where solar wind plasma merges with the Earth's magnetospheric plasma [Mozer, et al, 2002]. During a 28 s transit, the Polar spacecraft sampled the reconnecting magnetic field ($B_z = \pm 100\ nT$) as well as two lobes of an out-of-plane quadrupole magnetic field not predicted in the MHD theory. The two lobes were about 4 δ_i apart and the reconnection layer was at the ion inertial scale as predicted by the two-fluid theory.

Spheromak merging experiments were performed at SSX to verify this observation in the laboratory. Force-free spheromaks were merged and the full three-dimensional structure of the reconnection zone was mapped with 600 magnetic probes in a $5 \times 5 \times 8$ grid (the full vector $\mathbf{B}$ at 200 locations) [Matthaeus, et al, 2005]. SSX plasmas have densities about $n \sim 10^{20}\ m^{-3}$ and temperatures $T_i \geq T_e \sim 20\ eV$. The ion inertial scale and reconnection layer are about 2 cm and the ion mean free path is about 10 cm. Typical magnetic fields are about 0.1 T. Laboratory experiments allow us to probe the entire reconnecting structure at the same time whereas space observations must rely on only a few probes to sample a structure along a trajectory. In the SSX experiment, the full quadrupole structure was observed with each lobe about 4 δ_i apart. The reconnection layer was also measured at the ion inertial scale as predicted by the two-fluid theory. A key aspect of the experiment was that fully relaxed spheromak plasmas were merged in a high vacuum environment without vacuum magnetic fields or neutral gas present.

A similar experiment was performed on the MRX device [Ren, et al, 2005]. In this experiment, it was determined that the two-fluid effects (quadrupole, faster reconnection rate) were more pronounced as collisionality dropped. The merging plasmas were not fully three-dimensional relaxed spheromaks but quasi two-dimensional plasmoids. One dimensional arrays of 71-channels and 29-channels as well as a 90-channel 2D probe array were used. A key observation in this experiment was that the out-of-plane quadrupole magnetic field was largest in a low collisionality regime (reconnection width $\delta \leq \lambda_{MFP}$) but vanished at high collisionality ($\lambda_{MFP} \leq \delta$). It is clear that two-fluid or Hall physics is at play in collisionless plasmas.

Dynamo: The essential idea of the magnetohydrodynamic dynamo [Moffatt, 1978] is that an electrically conducting fluid moving in the presence of a magnetic field can generate a current. If that current generates a magnetic field in the same direction as the existing field, the magnetic flux is amplified. The source of the electromotive force is correlated motions or fluctuations of the velocity and magnetic fields ($\langle \mathbf{v} \times \mathbf{B} \rangle$). The dynamo mechanism is used to explain the observation of long-lived, large scale magnetic field in astrophysical objects like the Sun and planets. From a kinematic perspective, the process is called "stretch-twist-fold": a closed flux tube is stretched, twisted, then folded on itself by prescribed flows to amplify the magnetic flux. In a plasma dynamo experiment, it is important to separate cause and effect. It is certainly possible for electromagnetic fields to cause motion (as in a motor). Velocity fields and magnetic fields can be correlated but a dynamo requires that free motions of the plasma cause magnetic field to grow.

In the early 1990s, the magnetohydrodynamic dynamo was studied in SPHEX spheromak [al-Karkhy, et al, 1993]. The SPHEX spheromak operated at $n = 4 \times 10^{19}\ m^{-3}, B \cong 0.1\ T$, and $T_e = 20\ eV$. These parameters are in the collisional regime since the mean free path is smaller than the machine size ($\lambda_{MFP} \ll \ell$). The SPHEX group identified two types of MHD dynamo present in spheromaks: a "single-mode" dynamo in which a large scale motion contributes to the $\langle \mathbf{v} \times \mathbf{B} \rangle$ electromotive force and a turbulent dynamo in which correlated fluctuations of the $\mathbf{v}$ and $\mathbf{B}$ fields gave rise to an average dynamo electromotive force. The findings of the SPHEX group were that the magnitude of the turbulent dynamo was comparable to that required to drive toroidal current at the magnetic axis. The single-mode activity gave rise to an "anti-dynamo" opposing the externally applied electric field. More research could be done in this area, in particular measurements to verify cause and effect in the dynamo.

More recently, the two-fluid or Hall dynamo has been measured on the MST reversed field pinch (closely related to spheromaks) [Ding, et al, 2003 and 2004]. The MST RFP operates in a collisionless regime ($10^{19}\ m^{-3}, T_e \sim 300\ eV, \lambda_{MFP} \gg \ell$) so one would expect two-fluid effects to play a role. In this case, the source of the electromotive force is correlated motions or fluctuations of the current and magnetic fields ($\langle \mathbf{J} \times \mathbf{B} \rangle$). A novel multi-chord laser-based Faraday rotation diagnostic was used to measure the fluctuating magnetic field $\tilde{\mathbf{B}}$. The fluctuating current was then calculated from differences of adjacent line integrals of $\tilde{\mathbf{B}}$ and Ampere's law. The MST group determined that the Hall electromotive force in the mean magnetic field direction is large near the $m = 1$ mode surface. The Hall dynamo was found to be the main mechanism for redistributing current during relaxation events in MST. Such measurements have not been performed in a spheromak plasma though measurements in SSX show Hall terms to be larger than resistive terms in the generalized Ohm's law [Cothran, et al, 2005].

Future work in the ITER era: In the coming decade, an important role for spheromak research will be to continue to understand the physics of magnetic reconnection and the dynamo but to access smaller spatial and temporal scales in a collisionless regime. We are beginning to understand the importance of physics at the ion and electron inertial scales for both processes. In present spheromak merging experiments, the mean free paths are comparable to the machine size and the inertial scales are small. It will be interesting to study spheromak merging at higher temperatures and lower densities so that ion and electron mean free paths become long and two-fluid effects become important. It is clear that in solar and magnetospheric reconnection, the plasmas are collisionless so two-fluid effects should be considered.

References:

1. E. Priest and T. Forbes, "Magnetic Reconnection: MHD Theory and Applications", Cambridge University Press, Cambridge, UK, 2007

2. M. R. Brown, "Experimental Studies of Magnetic Reconnection", *Phys. Plasmas* **6**, 1717 (1999).

3. C. D. Cothran, M. Landreman, M. R. Brown, and W. H. Matthaeus, "Generalized Ohm's Law in a 3D Reconnection Experiment", *Geophysical Research Letters* **32**, L03105 (2005).

4. M. R. Brown, C. D. Cothran, and J. Fung, "Two Fluid Effects on 3D Reconnection in the SSX Experiment with Comparisons to Space Data", *Physics of Plasmas* **13**, 056503 (2006).

5. F. S. Mozer, S. D. Bale, and T. D. Phan, "Evidence of Diffusion Regions at a Subsolar Magnetopause Crossing", *Phys. Rev. Lett.* **89**, 015002 (2002).

6. W. H. Matthaeus, C. D. Cothran, M. Landreman, and M. R. Brown, "Fluid and Kinetic Structure of Magnetic Merging in the Swarthmore Spheromak Experiment", *Geophysical Research Letters* **32**, L23104 (2005).

7. Y. Ren, M. Yamada, S. Gerhardt, H. Ji, R. Kulsrud, and A. Kuritsyn, “Experimental Verification of the Hall Effect during Magnetic Reconnection in a Laboratory Plasma”, *Phys. Rev. Lett.* **95**, 055003 (2005).

8. H. K. Moffatt, “Magnetic Field Generation in Electrically Conducting Fluids”, Cambridge University Press, Cambridge, UK, 1978.

9. A. al-Karkhy, P. K. Browning, G. Cunningham, S. J. Gee, and M. G. Rusbridge, “Observations of the magnetohydrodynamic dynamo effect in a spheromak plasma”, *Phys. Rev. Lett.* **70**, 1814 (1993).

10. W. X. Ding, D. L. Brower, S. D. Terry, D. Craig, S. C. Prager, J. S. Sarff, and J. C. Wright, “Measurement of Internal Magnetic Field Fluctuations in a Reversed Field Pinch by Faraday Rotation”, *Phys. Rev. Lett.* **90**, 035002 (2003).

11. W. X. Ding, D. L. Brower, D. Craig, B. H. Deng, G. Fiksel, V. Mirnov, S. C. Prager, J. S. Sarff, and V. Svidzinski, “Measurement of the Hall Dynamo Effect during Magnetic Reconnection in a High-Temperature Plasma”, *Phys. Rev. Lett.* **93**, 045002 (2004).